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GEOPHYSICAL EFFECTS OF THE TRAPPED PARTICLE LAYER

Robert Jastrow
Theoretical Division, Goddard Space Flight Center
National Aeronautics and Space Administration
Washington, D. C.

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During the course of the International Geophysical Year the rocket and satellite programs of the US and USSR yielded a substantial amount of data on the properties of the ionosphere and the density and temperature of the upper atmosphere. These measurements and subsequent satellite observations have revealed several features which promise to broaden our understanding of the dynamics of the upper atmosphere. Perhaps most significant among these results is the evidence indicating that atmospheric properties in the auroral zone are influenced by the intensity of particles in the outer Van Allen belt.

Analysis of Satellite Orbits

The density of the atmosphere is determined from satellite tracking data by an indirect method, based on the analysis of changes in the period of revolution of the satellite. The change in the orbital period is a direct result of atmospheric drag, which causes the satellite to lose energy continuously during its lifetime. As the energy of the satellite decreases, it falls towards the center of the earth, increasing its velocity, and reducing its average altitude, and therefore reducing the time required to complete each circuit. Detailed calculations, based on the equations of satellite motion, then determine the quantitative relation between the reduction in the period and the average air density in the orbit.

Since the density falls off very rapidly with increasing altitude, the drag force is concentrated at perigee, the lowest point in the orbit. Thus the satellite density determinations are heavily weighted by the contributions from perigee. The loss of energy suffered during each pass through perigee results in a reduction in altitude attained on the next swing through the apogee, or highest point in the orbit. Thus the density at perigee determines the rate of decrease of the altitude at perigee. Conversely, the density at apogee is found to determine roughly the rate of decrease of perigee altitude. In the case of

the Vanguard I satellite, whose perigee and apogee heights are 650 km and 4000 km, respectively, the ratio of densities at perigee and apogee is approximately a factor of 100 according to reasonable atmospheric models. Since the apogee height of Vanguard I is decreasing at the rate of 10 km/year, we expect the perigee height for this satellite to decrease at the rate of only 100 meters/year. It has been found by O'Keefe, Bailie and Musen that when all known gravitational effects are removed in the analysis of the Vanguard I orbit, there remains a decrease of approximately one km/year in the perigee height. Apparently the drag at apogee is some 10 times larger than expected.

Satellite Drag Fluctuations

The satellite density data demonstrate large fluctuations over periods of a few days or weeks, when the accuracy of the tracking data is sufficient to permit the determination of orbital changes in such relatively short intervals (Jacchia, 1959; King-Hele and Walker, 1959). Figure 1 shows an example of the time variations in drag as calculated by Jacchia from the optical data on Sputnik III and Vanguard I. The agreement between the two sets demonstrates that the drag fluctuations are associated with changes in atmospheric conditions, rather than variations in the effective area or other characteristics of the satellite itself. These variations are probably the result of atmospheric heating produced by radiation and particle streams from the surface of the sun. If energy is transferred from the particle streams and radiation to the atmosphere, the resultant heating and temperature rise will cause an upward expansion, producing a large relative increase in the density of the air at high altitudes. It is known that in active perids the surface of the sun frequently emits such large gusts of plasma and radiation into the solar system.

Priester (communication to the Smithsonian Astrophysical Observatory, December 18, 1958) has pointed out that the apparently random fluctuations in the drag are actually proportional to the changes in the intensity of the 20 cm radiation from the sun, which constitutes an excellent measure of solar surface activity.

Furthermore, this correlation has been confirmed by Jacchia in the case of the 10 cm radiation. Jacchia has also remarked that the fluctuations show a tendency to repeat every 27 days, which is the period of rotation of the sun about its axis. Thus it appears that in addition to the heating and expansion of the atmosphere produced by steady solar exposure, there is further heating caused by streams coming from definite spots on the surface of the sun, which come around every 27 days in the course of its rotation.

In certain cases, those following major solar flares, the increase in drag acting on Sputnik III has been tentatively identified with the arrival of corpuscular streams in the vicinity of the earth (Jacchia, 1959a). Jacchia's results are presented in Figure 2, which shows that the drag increase on Sputnik III observed at the time of a major solar flare did not occur simultaneously with the flare, but began approximately one day later at the same time that the magnetic K index spurted upward. A rise in the K index signifies the onset of a magnetic storm, and therefore the arrival in the auroral region of the relatively slow-moving solar corpuscular stream which accompanies the flare. These solar particles are directed by the geomagnetic field in auroral latitudes where they may transfer energy to the atmosphere by mechanisms such as that discussed below. Sputnik III passes through the auroral zone and was apparently affected by the heating and expansion of the atmosphere in that region.

Jacchia (1959b) has refined his calculations to the point where he can say ultraviolet radiation is probably the cause of the recurrent drag variations which follow the course of the 10 cm solar flux. This statement is based on the fact that the drag fluctuations are largest when the perigee of the satellite is on the sunlit side of the orbit. When the perigee is in darkness the fluctuations become smaller or disappear. On the other hand, the fluctuations which accompany flares and magnetic storms seem definitely to be of corpuscular origin, as noted above.

The Rocket Data

Rocket measurements of the density at Fort Churchill (59°N) in the auroral zone, at altitudes up to 200 km, show that the atmosphere is about six times denser there than at corresponding altitudes over the White Sands Proving Ground in New Mexico (33°N) (LaGow, 1958; Townsend and Meadows, 1958). The same measurements show that the air over the auroral zone is also warmer at an altitude of 200 km with a temperature of approximately 2200°K as compared to 1100° K at White Sands (Horowitz and LaGow, 1957, 1958). The White Sands and Fort Churchill data were obtained from only two rocket flights, separated by an interval of eight years, and may not give a representative picture of conditions in the upper atmosphere. However, LaGow's results have been reinforced by a still more recent flight carried out at Fort Churchill last fall, in which the temperatures and densities were again found to be substantially greater than had been measured in the White Sands flight (LaGow, 1959). Figure 3 shows the comparison of temperatures obtained in these flights, as derived from the scale height data of LaGow, et. al. Spencer has also reported correspondingly high temperatures for ionospheric electrons above Fort Churchill (Spencer 1959).

Heating by Van Allen Particles

The particles in the Van Allen belt may provide the explanation for the difference between densities measured at White Sands and Fort Churchill. The Van Allen particles are trapped by the geomagnetic field in orbits in which they spiral along the lines of magnetic force. As Figure 4 indicates, the particles in the outer belt are funnelled into the arctic and antarctic zones by the concentration of the magnetic field near the north and south poles. The outer belt dips down into the atmosphere in these regions and disturbs the normal conditions which exist at lower latitudes.

The interaction between the trapped particles and the atmosphere can produce several geophysical effects. First, the temperature of the auroral zone will be raised by the energy transferred in collisions between the atoms and molecules of the upper atmosphere and the trapped particles in the outer belt. Second, the auroral borealis and the auroral australis may result from the excitation of the arctic and antractic atmospheres by these same collisions with the particles trapped in the outer zone.

Suggestions on the heating of the upper atmosphere by the channelling of charged particles in the geomagnetic field predate the discovery of the Van Allen belts (LaGow, 1958). Van Allen, McIlwain and Ludwig returned to these possibilities in their first discussion of the Explorer IV data, in which they suggested that the trapped particles may produce both auroral excitations and atmospheric heating (Van Allen, 1959). USSR scientists have made similar suggestions in their interpretation of the results from Sputnik III (Krassovsky, 1958).

The Van Allen data, supplemented by Sputnik III results and by rocket measurements performed by the Naval Research Laboratory and the State University of Iowa, now provide an opportunity for a theoretical examination of these interesting ideas. We have undertaken preliminary calculations based on an idealized model which confines the heating effect of the Van Allen layer to a definite region in the auroral zone, of width 500 km, whose boundaries are kept at a "temperate" level of 1000° K. The rate of heat transfer to the air within this zone is calculated from rocket and satellite observations on the energetic particles. We assume in the zone a heat source of Q $cal/cm^3/sec$, given by

$$Q = F \sigma \bar{E} n \qquad (1)$$

where

F = flux of energetic electrons;
σ = cross section for inelastic collisions;
$\bar{E}$ = energy transferred per collision; and
n = number density of atmospheric particles.

The flux of Van Allen particles must be taken from Sputnik III data, since the Explorer IV trajectory did not penetrate into the center of the auroral zone. From the Sputnik III results we have at present one datum, a reported energy flux of 4000 ergs/cm^2/sec/ster for electrons above 10 kev (Kràssovsky, 1958). This value is consistent with a figure of 10^{11} electrons/cm^2/sec at 16000 km in the heart of the outer zone, reported by Van Allen on the basis of the Pioneer flights (1959a). It refers to an altitude over the USSR which may be estimated at 300 km from our knowledge of the Sputnik III orbit. At 300 km, $n \gtrsim 2.5 \times 10^{-9}$/cm^3. Finally, at 10 kev the cross section (σ) for inelastic collisions is approximately 10^{-18} cm^2, and the kinetic energy ($\bar{E}$) available in each collision is $\simeq 20$ ev (Fite, private communication).

Using the values given above, we find $Q \gtrsim 4 \times 10^{-16}$ cal/cm^3/sec at 300 km. Equation (1) shows that the heat source is independent of altitude, if we assume that the trapped particle flux varies in inverse proportion to the number density for atmospheric particles. This assumption must break down at very high altitudes, and in our calculations we therefore cut off the source at various heights between 400 and 600 km. The magnitude of the temperature changes is not sensitive to this choice as long as the heated region is at least several hundred kilometers in vertical extent.

Recent rocket observations suggest an additional source of excitation at the time of auroral displays. The rocket experiments were performed by Meredith, et al. of the Naval Research Laboratory and McIlwain of the State University of Iowa (Meredith, Davis, Heppner, and Berg, 1958; McIlwain, 1958). They indicate that in the auroral zone and at the time of an aurora there is a substantial flux of energetic electrons, with roughly constant intensity between 100

and 180 km. These energetic electrons have a uniform angular distribution over the upper hemisphere. In this respect, they differ from the trapped Van Allen particles, whose angular distribution is concentrated in the plane perpendicular to the local direction of the magnetic field. The isotropic distribution of the electrons observed in the rocket experiments suggests that they are not trapped electrons, but rather those electrons which have been removed from the trapped particle layer by multiple scattering, and which now wander down through the atmosphere beneat the lower border of the trapped particle zone. As we have noted, the flux (F) of this group of electrons is observed to be roughly independent of altitude. According to (1) their rate of energy transfer therefore varies only with atmospheric density (n). Hence the corresponding heat source is a sharply increasing function at lower altitudes. The superposition of this source on the altitude-independent source produced by the trapped electrons leads to the curve at the right hand side of Figure 5.

The isotropic electrons do not make a significant contribution to the magnitude of the calculated temperature increase. However, they do produce a more rapid rise of temperature between 120 and 180 km than would be obtained from the trapped electrons alone.

The equation of heat conduction, $Q = K\nabla^2 T$, may be solved analytically with the indicated boundary conditions. I. Harris and the writer have shown in this way that the temperature must rise to approximately 2500° K at the center of the auroral zone, in agreement with LaGow's data. The transport of heat across the zone boundaries in this model amounts to approximately one erg/cm^2/sec.

The close agreement with observation is fortuitous in view of the approximations made in calculating the heat source and in the construction of the boundary value problem. However, it is significant that the temperature increase has the correct order of magnitude. The

calculations have recently been repeated by Harris with a more realistic treatment of the boundary value problem, and with results substantially the same as those given above.

Convection Transport

In our first calculations we neglected the transport of energy by convection. However, an estimate of convective transport indicates that it will dominate over conduction at altitudes below 400 km. We have therefore carried out an approximate calculation of the temperature increase in the auroral zone assuming convective transport only, and using the previous value of 4×10^{-16} cal/cm^3/sec for the heat source. The results indicate that the temperature will rise by 400° between 200 and 400 km, in contrast to the increase of 1500° obtained in the conduction calculation. It is clear that convective transport may be an important feature of the atmospheric changes produced by electronic heating, and there is a slight possibility that it may produce changes in the circulation of the lower atmosphere. We are therefore undertaking more elaborate calculations in which this mechanism is included.

Origin of the Aurora

Since the energy content in the Van Allen belt may be sufficient to make substantial changes in the temperature and density of the upper atmosphere and perhaps to account for the observed latitude effect in the rocket data, we are encouraged to look further into the possibility that the outer Van Allen belt also provides the origin for auroral phenomena. As a first step, I. Harris and the writer examined the data on the frequency of auroral events as a function of altitude, which have been collected and published by Störmer (1955). We presumed that if the Van Allen layer is the primary source of the aurora, then the rate of energy transfer from the Van Allen particles

to the atmosphere will also govern the altitude distribution of auroral displays. In Figure 5 we show on the right the heat source Q in calories/cm^3/sec, as estimated from the rocket and satellite data on the fluxes of energetic electrons, and applied to our studies of temperature variations in the upper atmosphere. On the left in Figure 5 we show the altitude distribution of 12,330 auroras, as reported by Störmer. We see that the intensity of energy transfer to the atmosphere and the frequency of auroral events both disappear below 90 kilometers and have a sharp maximum near 100 kilometers. In our view this correspondence strongly supports the suggested association between energetic electrons and auroral displays. Additional evidence of a very convincing character is supplied by the recent analysis of Vestine, in which it is shown that the theoretical properties of the trapped particles lead to an accurate prediction of auroral isochasms in the arctic and antarctic zones (Vestine, 1959).

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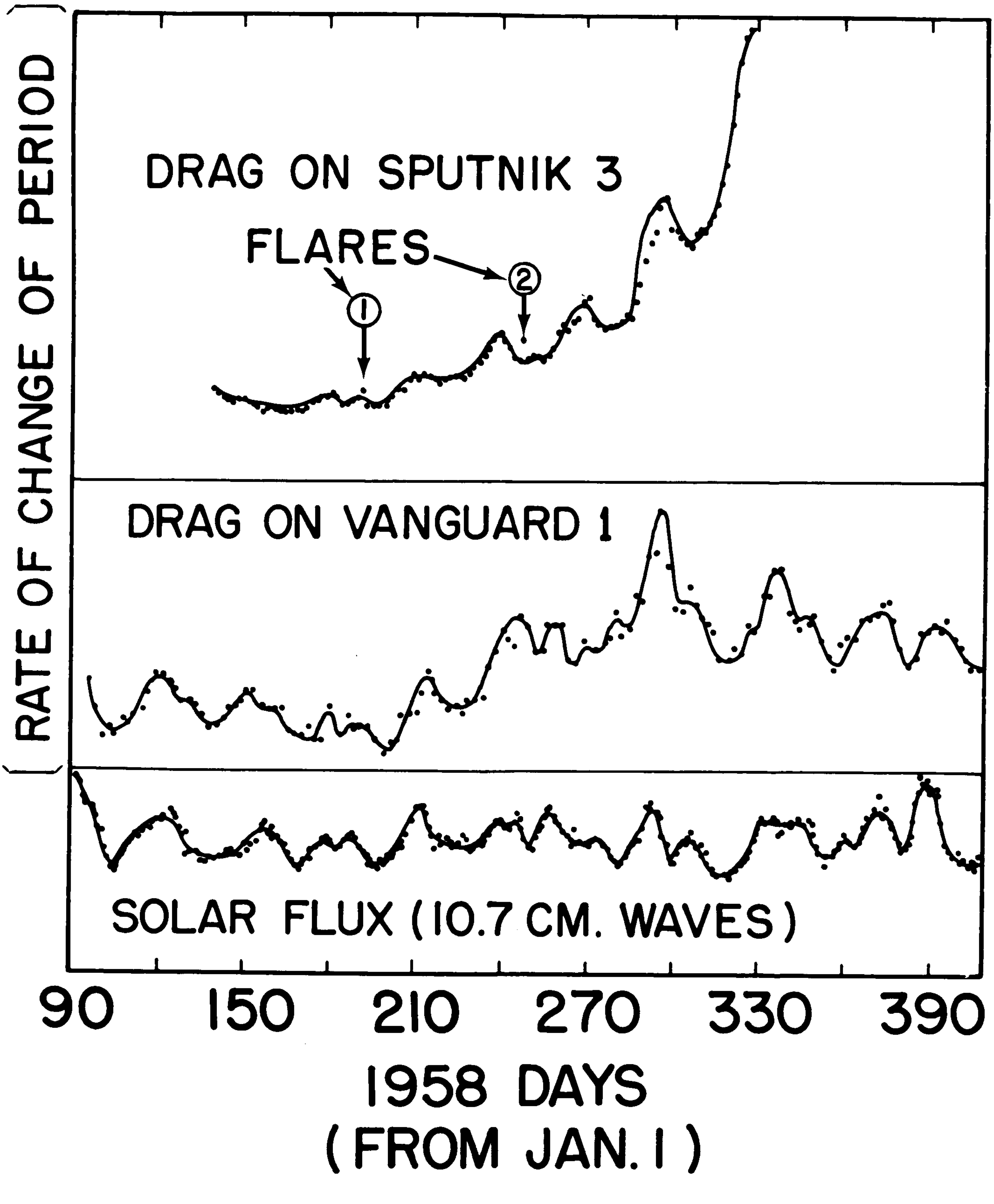
FIGURE 1.

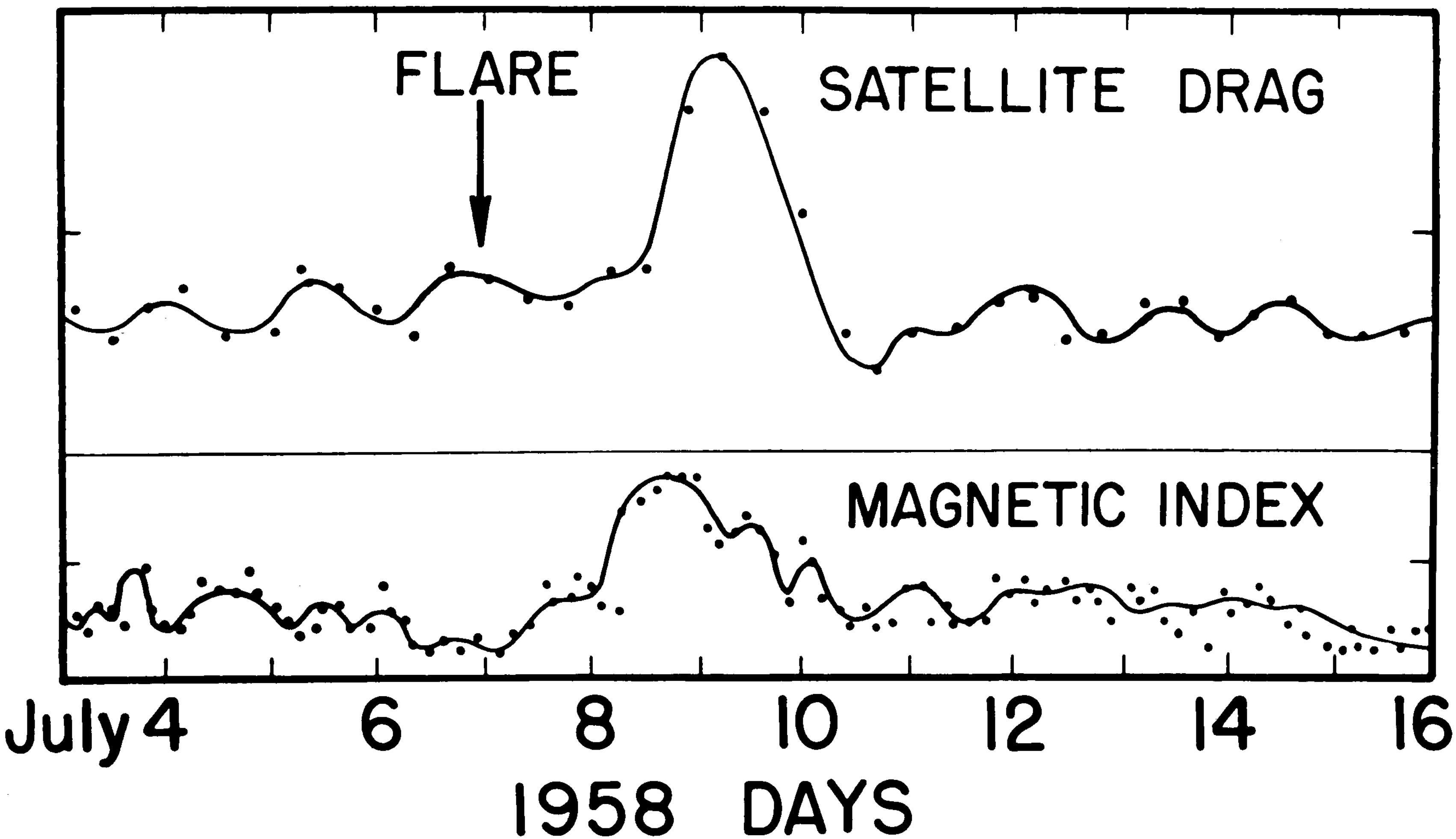
Solar effect on satellite drag.



RATE OF CHANGE OF PERIOD
DRAG ON SPUTNIK 3
FLARES
1
2
DRAG ON VANGUARD 1
SOLAR FLUX (10.7 CM. WAVES)
90
150
210
270
330
390
1958 DAYS
(FROM JAN. 1)

FIGURE 2.

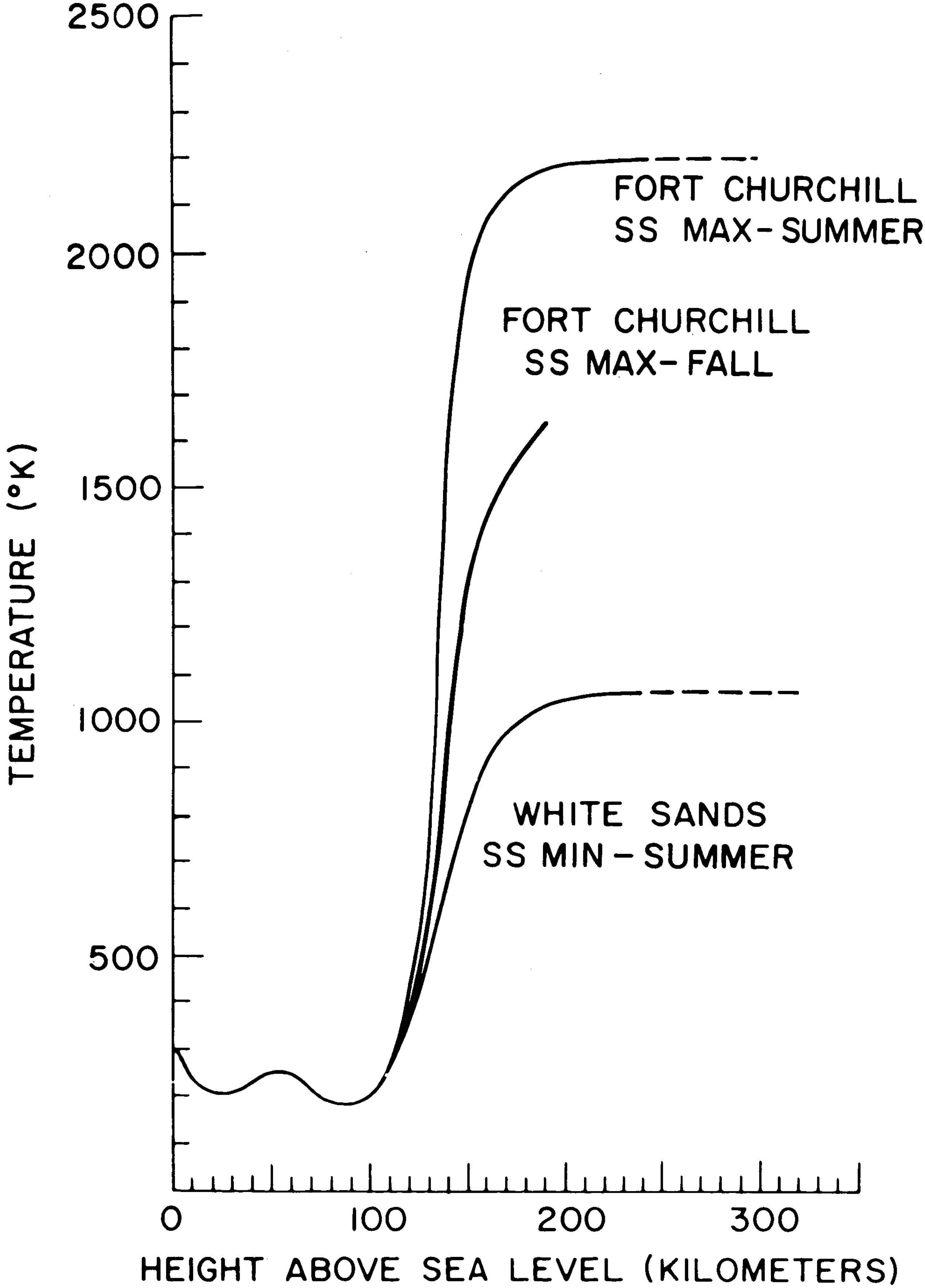
An example of the delay between occurrence of a solar flare and onset of the drag increase.



FLARE
SATELLITE DRAG
MAGNETIC INDEX
July 4
6
8
10
12
14
16
1958 DAYS

FIGURE 3.

Rocket measurements of upper atmosphere temperatures (after Horowitz and LaGow, 1958a, and LaGow, 1959).



2500
2000
1500
1000
500
TEMPERATURE (°K)
FORT CHURCHILL
SS MAX-SUMMER
FORT CHURCHILL
SS MAX-FALL
WHITE SANDS
SS MIN-SUMMER
0
100
200
300
HEIGHT ABOVE SEA LEVEL (KILOMETERS)

FIGURE 4.

Channelling of geomagnetically trapped particles into high latitudes.

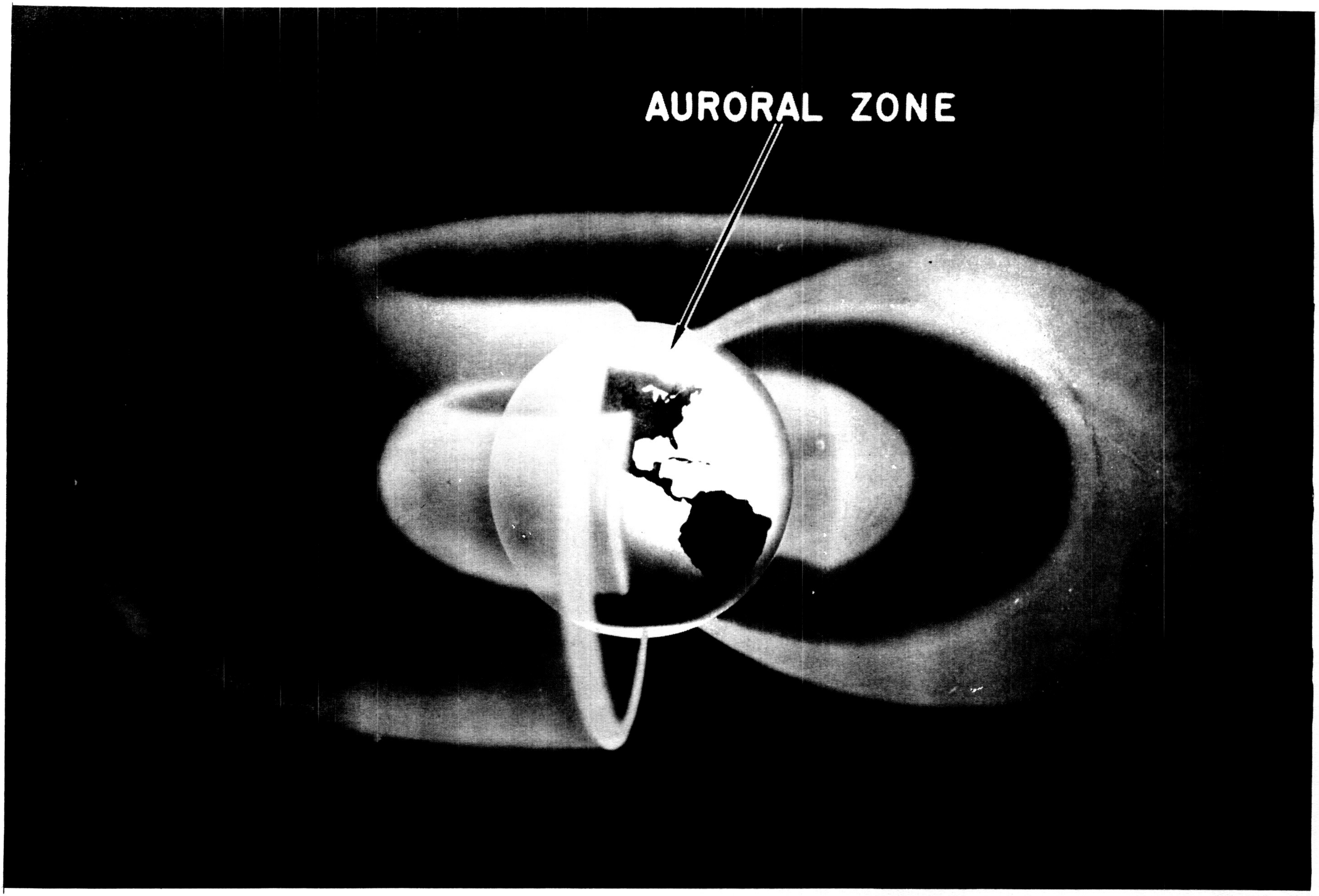
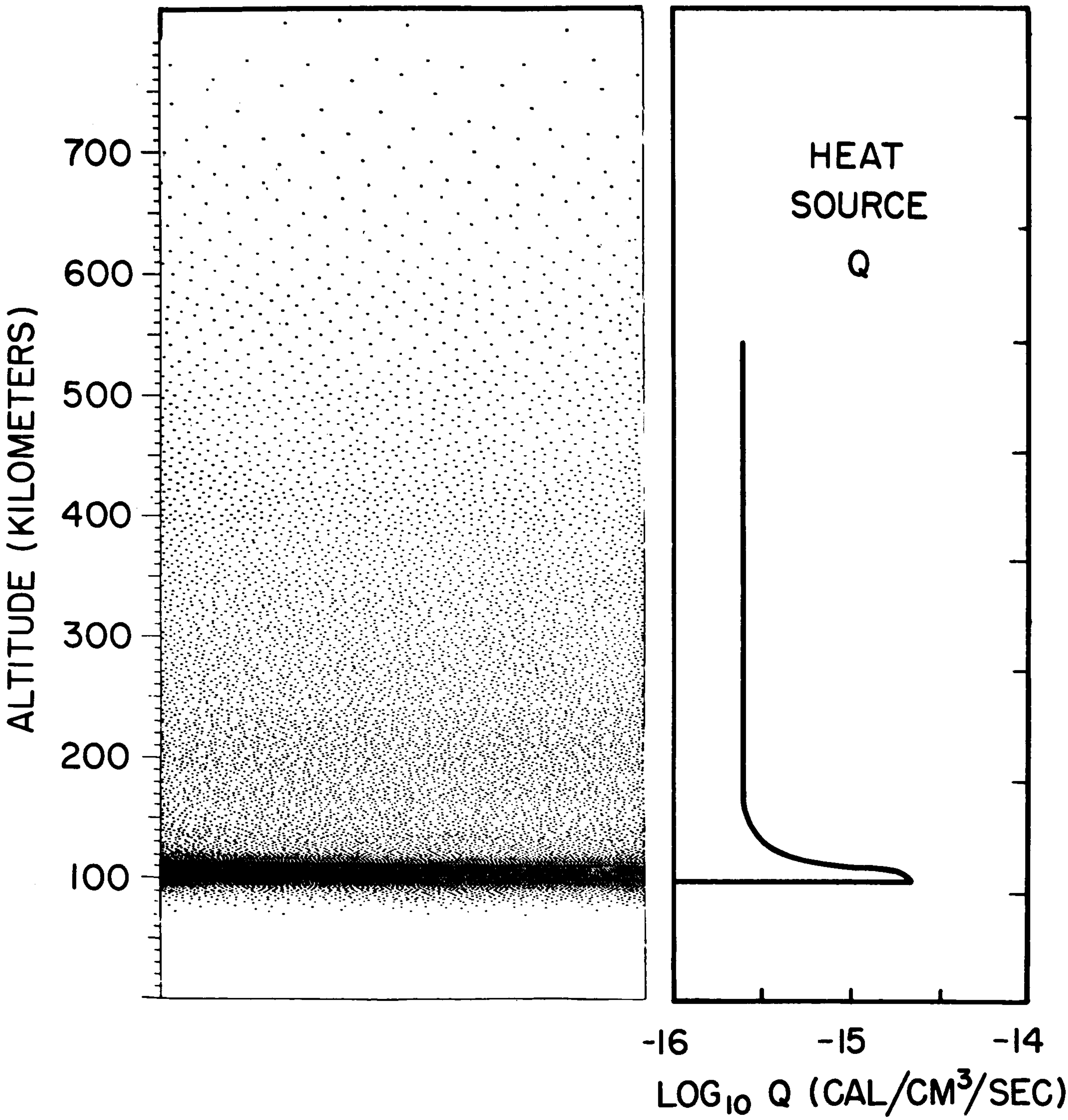

AURORAL ZONE

FIGURE 5.

Comparison between the distribution of auroral altitudes (left) and the calculated rate of energy transfer from energetic electrons to the atmosphere (right).



ALTITUDE (KILOMETERS)
700
600
500
400
300
200
100
HEAT
SOURCE
Q
-16
-15
-14
LOG10 Q (CAL/CM3/SEC)